Experiments on the Flow of Steam Through Small Pipes,

BY

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THESIS

For the Degree of Bachelor of Science in the School of

Mechanical Engineering, College of Engineering.

UNIVERSITY OF ILLINOIS.

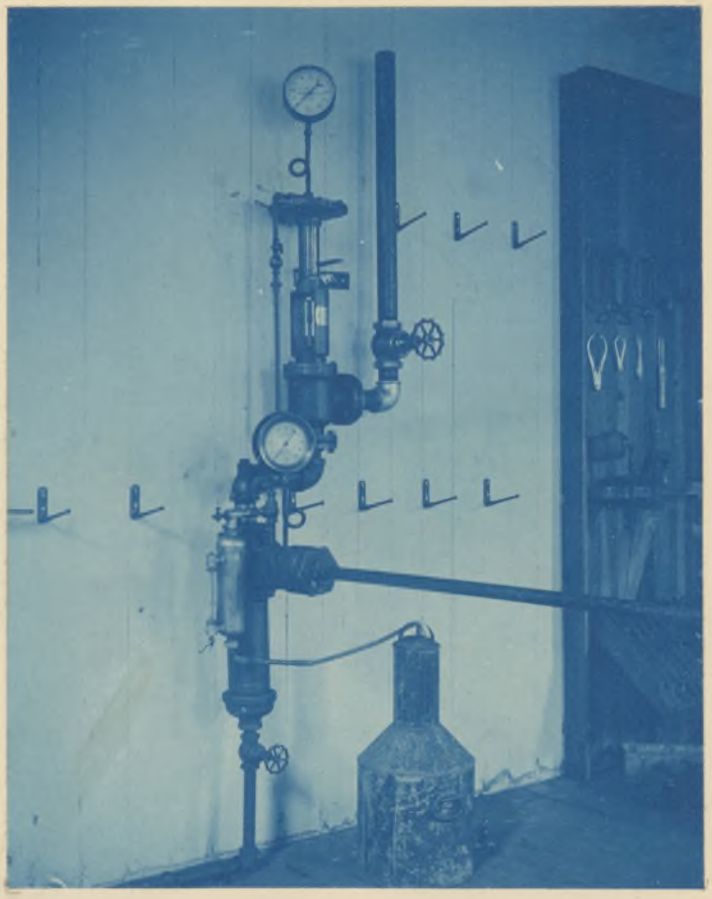
1896.

Experiments on the Flow of Steam

Through Small Pipes.

The following experiments were made at the Mechanical Engineering Laboratory at the University of Illinois to determine the weight per minute, and velocity of steam flowing through several sizes and lengths of small pipes, with a given loss of pressure.

The apparatus used in the experiments is shown in the photograph page 2, and consists of a receiver, a Fisher reducing valve, a calorimeter, two steam gages and a thermometer. The receiver was made of a tee and two short pieces of four inch steam pipe, as shown in the drawing page 3. A and G are reducing bushings for one and one-half inch pipe. B is a reducer for one inch pipe. Steam enters the receiver through the one and one-half inch pipe H, which extends twelve inches into the receiver. F is a 1 1/2 X 3/4 X 1 1/2 inch tee with a deep thermometer oil cup in the 3/4 inch end. L is the experimental pipe and is fitted into the bush G with reducers. The pressure in the receiver was observed on the gage at E. The gage on the reducing valve was also read as a check on the other. Both gages were Schaffer and Budenberg, Bourdon spring gages; the one on the receiver reading from 0 to 100 pounds and graduated to two pounds; the one on the reducing valve reading from 0 to 150 pounds and graduated to five pounds. The gages were calibrated by



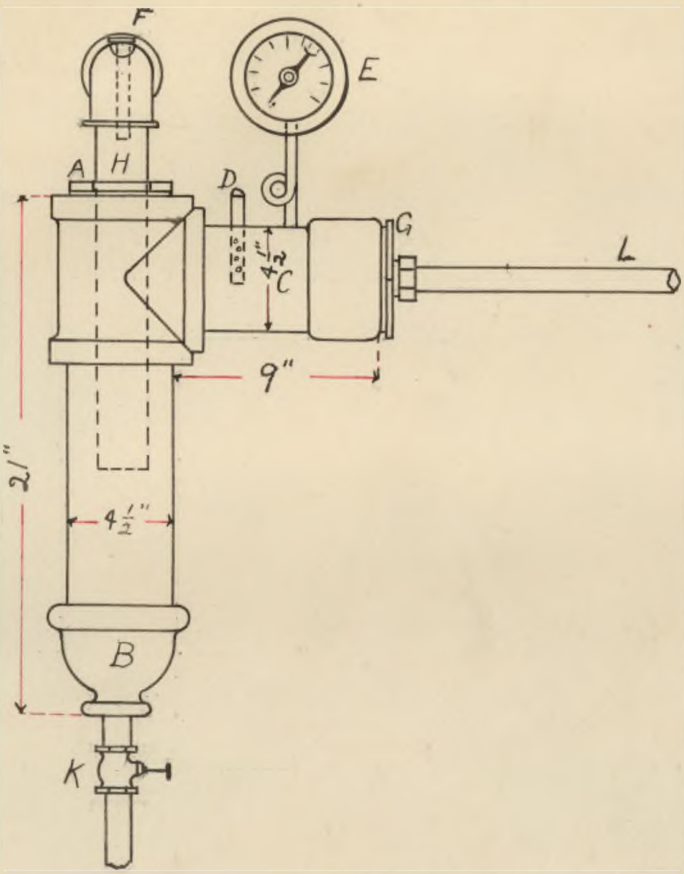


Fig. 1.

comparison with a Crosby steam gage tester before the experiments were begun, several times during the course of the experiments, and after they were completed; at each calibration the gages were found to be in good condition.

The pipes used in the experiments were standard size steam pipe and were used in the condition in which they came from the mill except that when they had to be cut with a hand cutter, the burr made by the cutter was reamed off. Straight pipes without valves or ells were used in all the experiments. The pipe was supported by iron brackets about 8 feet apart, placed on the window casings of the south side of the laboratory, and was laid with a fall of one inch in ten feet. The first 16 feet of pipe measuring from the receiver was inside of the boiler house, the next thirty feet was outside and 3 1/2 inches from the wall of the building, the remainder was 22 inches from the wall.

Boiler No. 1 of the M. E. Shop battery was used to supply steam for the experiments. The apparatus shown in the photograph was attached to the boiler by about twelve feet of one and one-half inch pipe and had a globe valve and two ells besides those shown. The pressure on the receiver was regulated to that at which it was desired to make the experiment, by throttling the steam with the globe valve, R, shown in photo on right side of reducing valve; there was no difficulty in maintaining the pressure very nearly constant in this way. As the reducing valve required considerable time to adjust it for different pressures it was not used after the first six or eight experiments were made; it was then adjusted so that the steam passed through without being reduced. The temperature of the steam was observed by the thermometer in the oil cup; in this way it was known whether the steam was superheated or not by the throttling. It was found, that if the steam was throttled so as to reduce the pressure 50 or 60 pounds, that it was usually superheated and for the rest of the experiments the boiler pressure was not more than 30 or 35 pounds above that at which the experiment was made.

The quality of the steam in the receiver was determined with a Carpenter Separating Calorimeter attached at D in the drawing. The collecting nipple extends 2 1/2 inches into the top of the receiver and is a 1/2 inch gas pipe with 1/8 holes drilled in it and the end closed. In operating the calorimeter, steam was allowed to flow through the separating vessel until the escaping steam looked dry; the hose to the condensing vessel was then connected and after steam had been condensing for a minute or two, readings of the scales were taken. Four or five observations of the scale readings were usually made during each experiment, all readings being made while the calorimeter was running; from this data three or four calculations of moisture were made and the average taken.

The weight of steam flowing was determined by reading the height of water on the gage glass at the beginning and end of an experiment and finding the weight of water used from a calibration curve for the boiler, then making corrections to this weight for moisture in the steam and for the difference in density of hot water and the cold water with which the boiler was calibrated, and for the weight of steam used by the calorimeter and removed as condensation at the receiver. All of the experiments, with the exception of two or three, were of from 35 to 40 minutes duration, but only the weight of steam flowing in thirty minutes was used in the calculations.

The data for the calibration curve was obtained by filling the boiler with cold water to a height of about ten inches on the gage and weighing it out, 50 pounds at a time, down to the zero of the scale. The height of water on the gage was read on a wooden scale graduated to tenths of inches, which was placed beside the gage glass. The curve in Fig. 2 was plotted from thisdata with inches on gage glass as abscissae and pounds of water as ordinates; it covers the range through which the height of water changed during the experiments. The boiler was also filled full of water and then all weighed out. The curve in Fig. 3 was plotted from this data; it checks very well with the curve in Fig. 2.

The curve in Fig. 2 was used in determining the weight of steam for the experiments. Before beginning an experiment the boil-

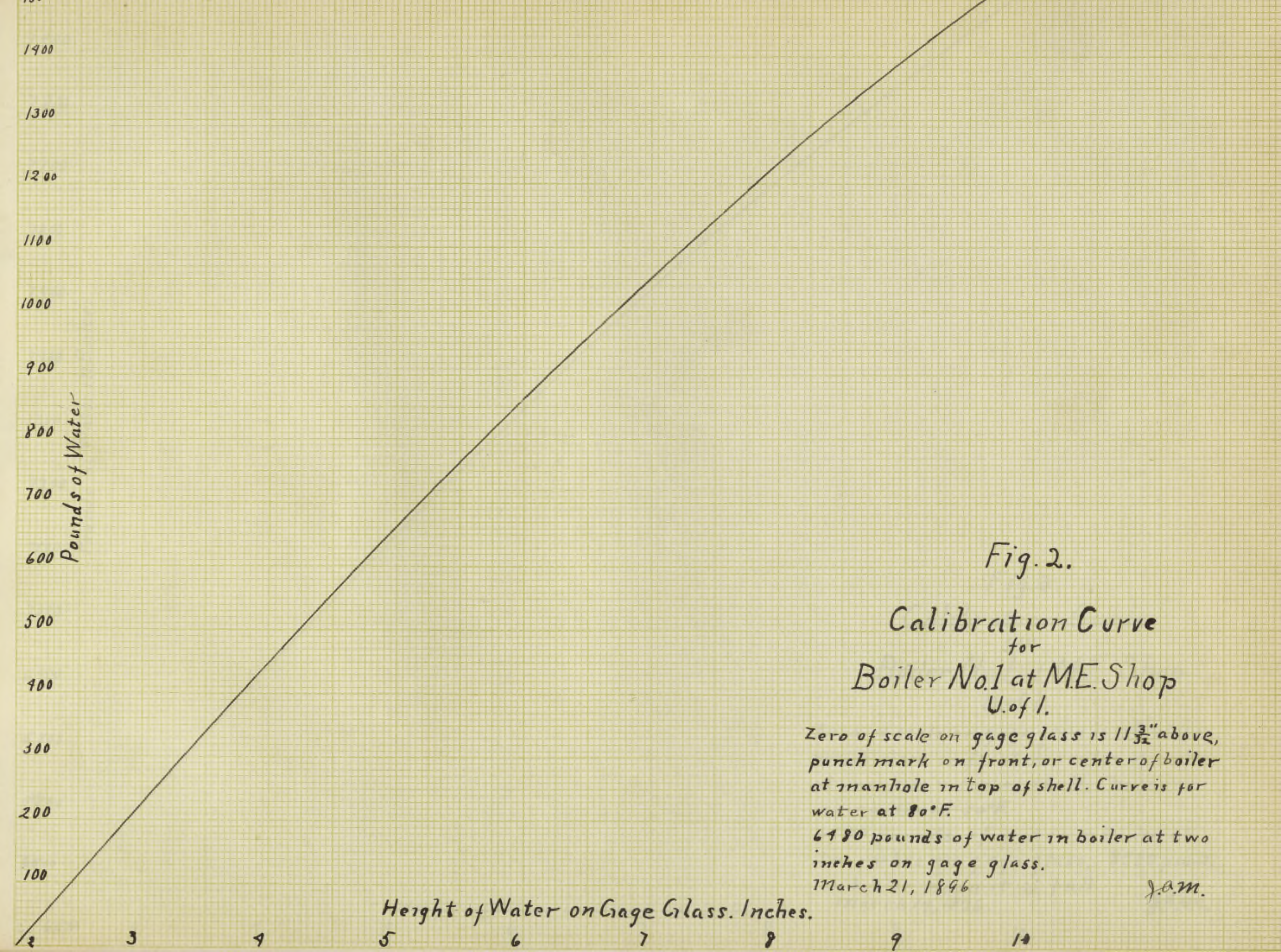


Fig. 2.

Calibration Curve
for
Boiler No.1 at M.E. Shop
U. of I.

Zero of scale on gage glass is $11\frac{3}{32}$" above, punch mark on front, or center of boiler at manhole in top of shell. Curve is for water at 80°F.

6480 pounds of water in boiler at two inches on gage glass.

March 21, 1896

J.O.M.

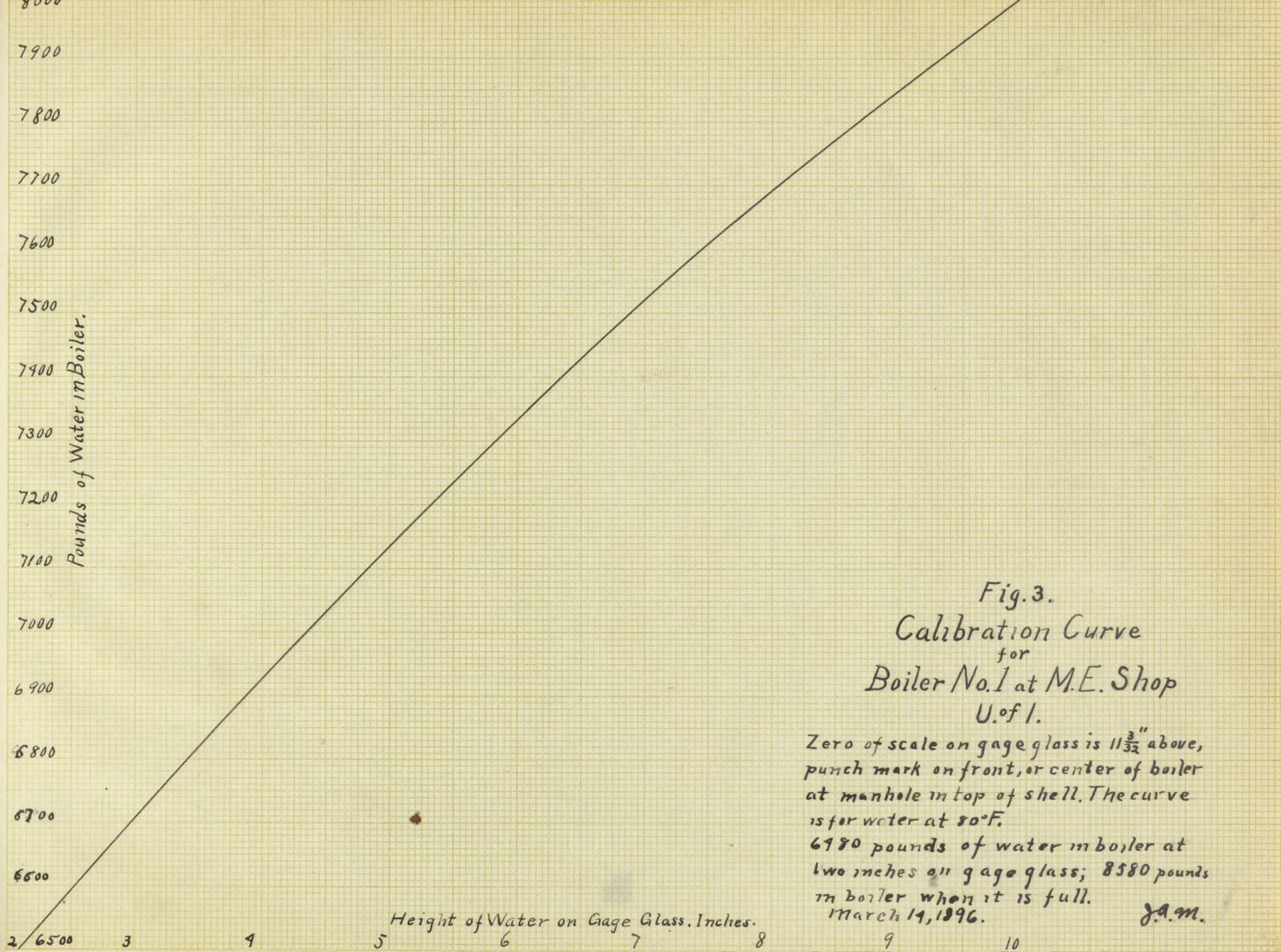


Fig. 3.
Calibration Curve
for
Boiler No. 1 at M.E. Shop
U. of I.

Zero of scale on gage glass is $11\frac{3}{32}$" above, punch mark on front, or center of boiler at manhole in top of shell. The curve is for water at 80°F.
6480 pounds of water in boiler at two inches on gage glass; 8580 pounds in boiler when it is full.

March 14, 1896.

J.A.M.

er was filled up to a height of about seven inches on the gage and steam allowed to flow through the apparatus. The pressure in the receiver was regulated to that at which it was desired to make the experiment, and the experiment begun after the apparatus had been running steadily for some time. In the first fifteen or twenty experiments the height of water was read every five minutes; in the remainder it was read every ten minutes. No water was put into the boiler during an experiment and the height of water was always read with the water going down. The blow off pipe was disconnected so that any leakage at that point could be detected; great care was taken to see that all valves were closed tight, so that no steam could get out of the boiler without going through the apparatus. The condensation which collected in the receiver was let out through the valve K shown in the drawing; the valve was set so as to leak slightly and the condensation and small amount of steam that escaped was caught by dipping the end of the drip pipe into a bucket of water. The weight of water obtained from the calibration curve was corrected for moisture in the steam by the results of the calorimeter experiments.

Several methods were tried to get at the correction to be made for the difference in density of the water. One method was to find what the per cent of the weight of a cubic foot of water, at temperatures corresponding to 30, 40, 50, 60, etc. pounds of pressure, was of the weight of a cubic foot at the temperature of the water used in calibrating the boiler. The curve A, Fig. 4 was plotted from this data. The weight per cubic foot of water at different temperatures was taken from a table given by Thurston in his "Engine and Boiler Trials". Another method was to fill the boiler with cold water to a height of six or seven inches on the gage and gradually raise steam up to 90 pounds pressure and reading the height of water for each ten pounds increase of pressure. The ratio of the weight of the hot water to the cold water was then obtained by dividing the total weight of water in the boiler at the beginning of the experiment by the weight of water obtained from the calibration curve for the heights of water on gage corresponding to the different pressures. The curves B_1 and B_2 (Fig. 4) were plotted from data obtained in this way. Although the two experiments give results very nearly alike, they seem to be too large compared with the results obtained by the first method.

After all of the experiments on the pipes had been completed a Wheeler Surface condenser had been put in the laboratory. It was connected to the boiler and experiments made by condensing the steam and weighing it in a tank. In making these experiments the boiler was filled as when making experiments on the pipes. The height of water on the gage was read each time the condensed steam was weighed. By dividing the weights obtained in this way by the

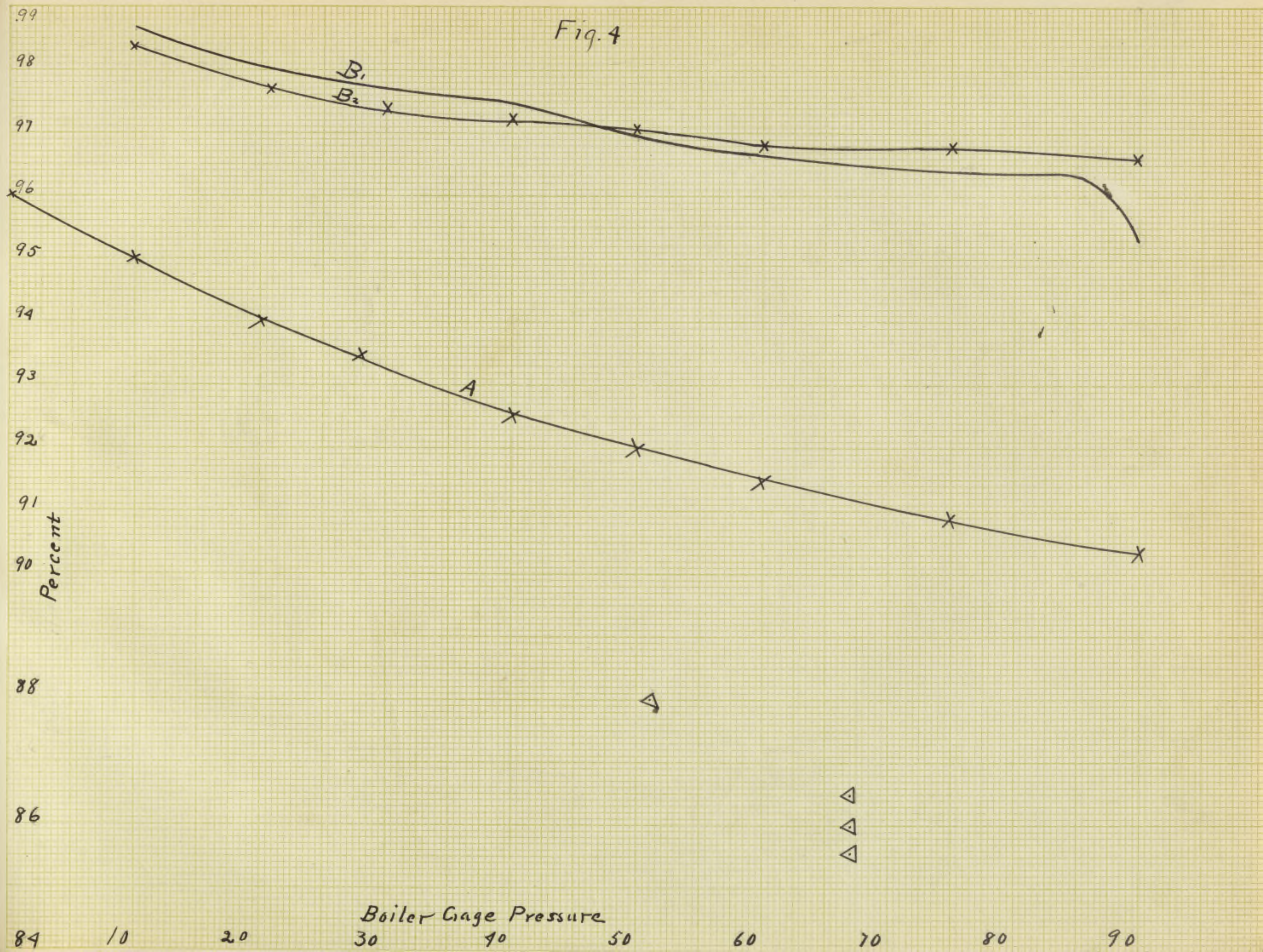


Fig. 4
B_1
B_2
A
Percent
Boiler Gage Pressure
99
98
97
96
95
94
93
92
91
90
88
86
84
10
20
30
40
50
60
70
80
90

weight obtained from the calibration curve for the corresponding heights on the gage, we get a ratio of the weight of the cold water to the hot. For fifty-one pounds boiler pressure the value obtained was .88; for 67 pounds, .855, .86 and .87. These points are marked (△) at the bottom of the diagram (Fig.4). The value for 67 pounds for the curve A is .912. As the conditions under which these last experiments were made are very nearly those at which the boiler was used, .87 was taken to make the correction on the weights obtained from the calibration curve. A calibration curve for the boiler could have been plotted with the weights obtained by condensing the steam, but as the pump did not work steadily, the water was not always drawn off as fast as it was condensed, and the curve would have been very irregular.

Experiments were made with pipes 3/4, 1, and 1 1/4 inches in diameter, 49 and 100 feet in length. Five experiments were made on a one-half inch pipe 49 feet in length but as the area of the pipe was reduced about 1/3 by a burr at one of the couplings, the results have not been used. Table 1 shows the different pressures at which experiments were made on each size and length of pipe. The pressures given in the table are the gage pressures observed on the receiver. The terminal pressure in all the experiments was that of the atmosphere.

The following forms of logs were kept during the experiments:

Log of Experiment No. 57. April 25, '96

Time	Receiver Gauge Pressure.	Reducing Valve Gauge Pressure	Height of Water on Gauge glass.ins	Boiler Gauge Pressure	Temperature of Steam. F.	Temperature of external air. F.
9:12	25	25	7.13	50	265	---
9.22	25	25	6.8	50	---	69
9.32	25	25	6.51	52	266	---
9.42	25	25	6.23	55	---	---

Calorimeter Log for Experiment No. 57.

Time	Height of water on scale of Separator.	Height of water on scale of Condensing Vessel.
9.30	3.7	.75
9.35	6.7	2.1
9.40	9.5	3.25

The data and results of the experiments are given in the following tables. The headings will explain the tables. The results of the experiments are plotted in the accompanying diagrams (Figs. 5 to 13). The formula from which the flow of steam per minute is calculated is

$$W = 87\sqrt{\frac{D(P_1-P_2)d^5}{L(1+\frac{3.6}{d})}}$$

in which W = the weight in pounds avoirdupois, d = diameter in inches, D = weight of steam per cubic foot; P_1 the initial pressure, P_2 the pressure at end of pipe and L the length of feet. This is an approximate formula said to have been proposed by Mr. Geo. H. Babcock; several tables for the flow of steam have been calculated from it. The actual diameters of the pipes as given by Briggs Standard were used in the calculations.

The velocity of the steam given in the tables were calculated by the formula

$$V = W \div (D \times a \times 60)$$

in which V = the velocity in feet per second, W = weight of steam in pounds per minute by experiment, D = weight of steam per cubic foot, a = area of pipe in square feet. The area of the pipe was taken from Briggs standard and reduced to square feet. In calculating the velocity at entrance of pipe the density of steam at receiver pressure was used; for the velocity at terminal of pipe the density at 15 pounds absolute was used and the steam assumed to be saturated although it may have been superheated, as no observations of the temperature were made. No account has been taken of condensation in the pipe, but it is probably small as the number of square feet of surface in the sizes of pipes used in the experiments is not large. Buel's Steam Tables were used for the properties of steam used in the calculations.

It should be noted that on account of the small cross section of the receiver that the steam would have a considerable velocity through the receiver, and that a higher velocity is probably attained through the pipe than would be produced by the pressure on the receiver.

From an inspection of the curves for the weight of steam flowing per minute it is seen that the observed flow is greater than the flow calculated by the formula in all but two cases; the exceptions are the experiments on the 100 foot length of 1 1/4 inch pipe and the experiment at 49 pounds on the 49 foot length of the same size. The curves for the experiments on the 100 foot lengths of all the pipes used are nearly parallel to the curves for the formula and differ but little from them. The results for the 49 foot lengths vary more from the results of the formula than do those of the 100 foot lengths. From the curve for 3/4 inch and the direction of the curves for 1, 1 1/4 inch pipes, 49 feet long it would seem that there is a pressure at which we would get a maximum flow, and that in the same way as for the flow of steam through orifices, increasing the pressure beyond this point would not increase the flow. By a comparison of the curves for the 49 and 100 foot lengths of pipe it appears that the difference of pressure required to produce a maximum flow depends upon the length, as there is no appearance of the curves for the 100 foot lengths changing this direction within the range of pressures at which the experiments have been made.

An inspection of the curves for velocity at the end of the pipes, show that the velocity gradually increases with the increase of the initial pressure. The curves for the velocity at the beginning of the pipes show that the velocity changes but little for a given size and length of pipe, when the pressure is increased; that for the 49 foot lengths a maximum velocity is reached and for further increase of pressure the velocity decreases. The maximum velocity for the 3/4 inch pipe is obtained with an initial pressure of 35 pounds; for the 1 and 1 1/4 inch pipes the maximum is reached at 25 pounds initial pressure. The velocity also slightly increases with the increase in the size of pipe.

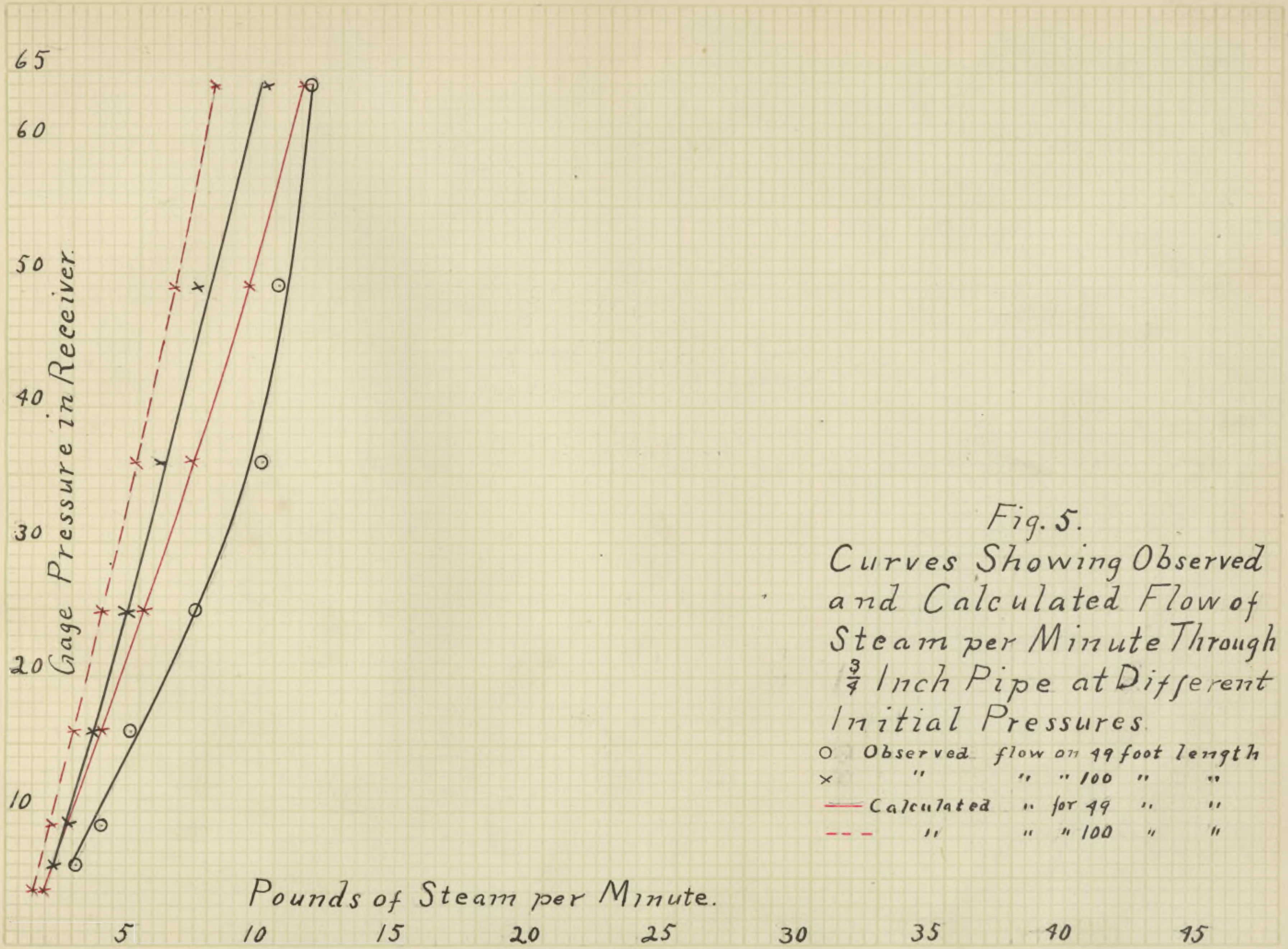


Fig. 5.
Curves Showing Observed and Calculated Flow of Steam per Minute Through $\frac{3}{4}$ Inch Pipe at Different Initial Pressures

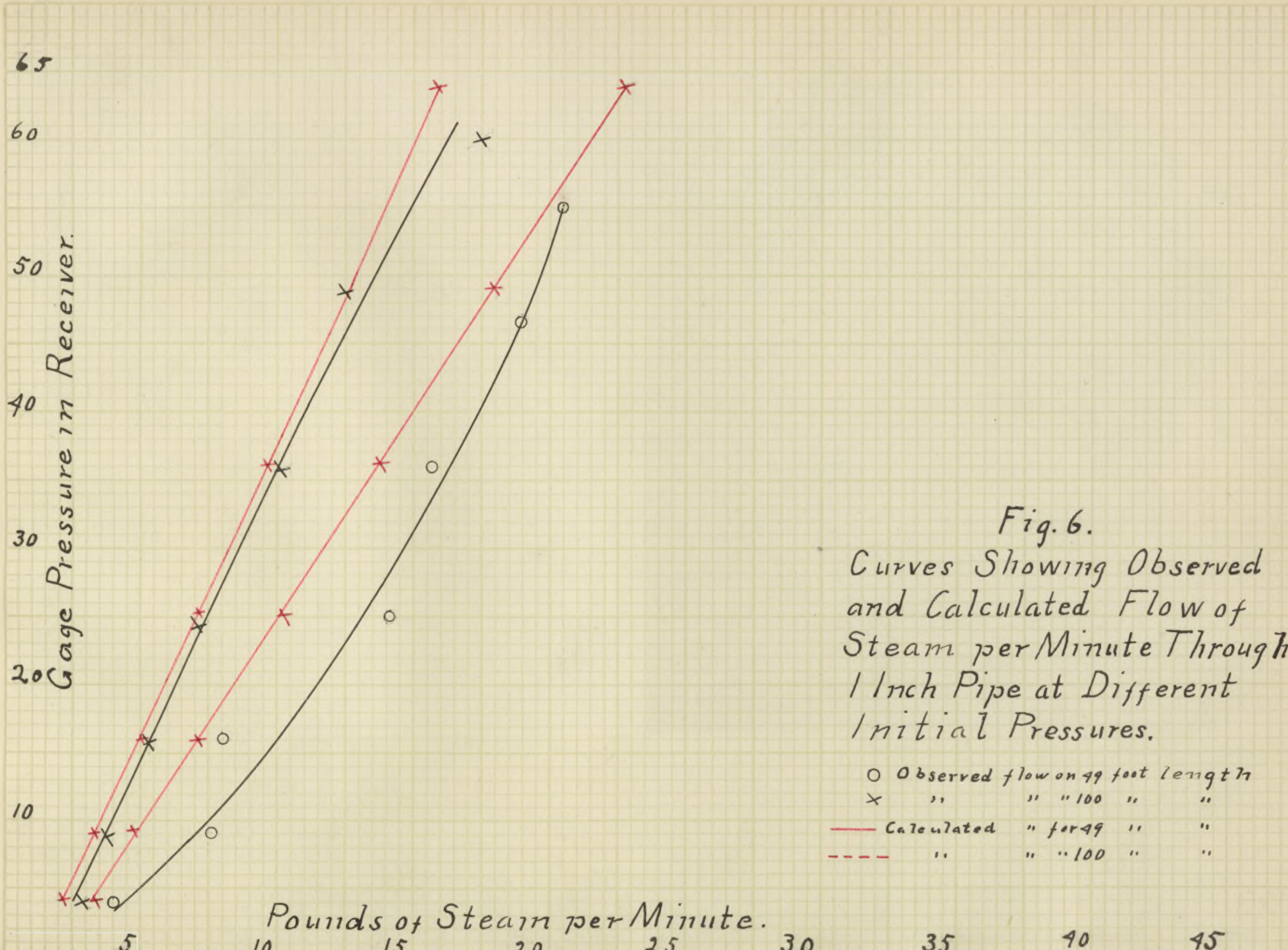


Fig. 6.
Curves Showing Observed and Calculated Flow of Steam per Minute Through 1 Inch Pipe at Different Initial Pressures.

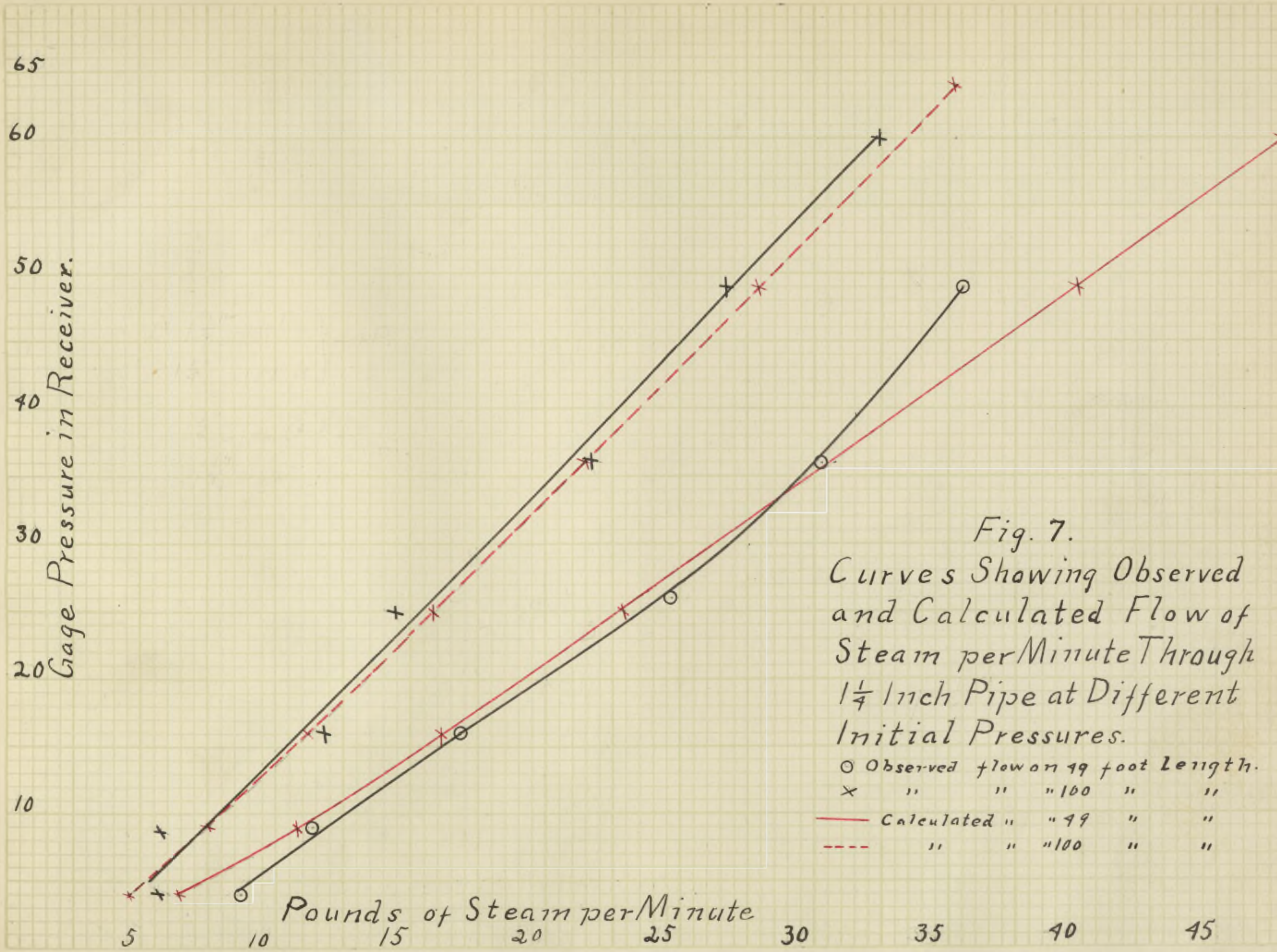


Fig. 7.
Curves Showing Observed and Calculated Flow of Steam per Minute Through $1\frac{1}{4}$ Inch Pipe at Different Initial Pressures.

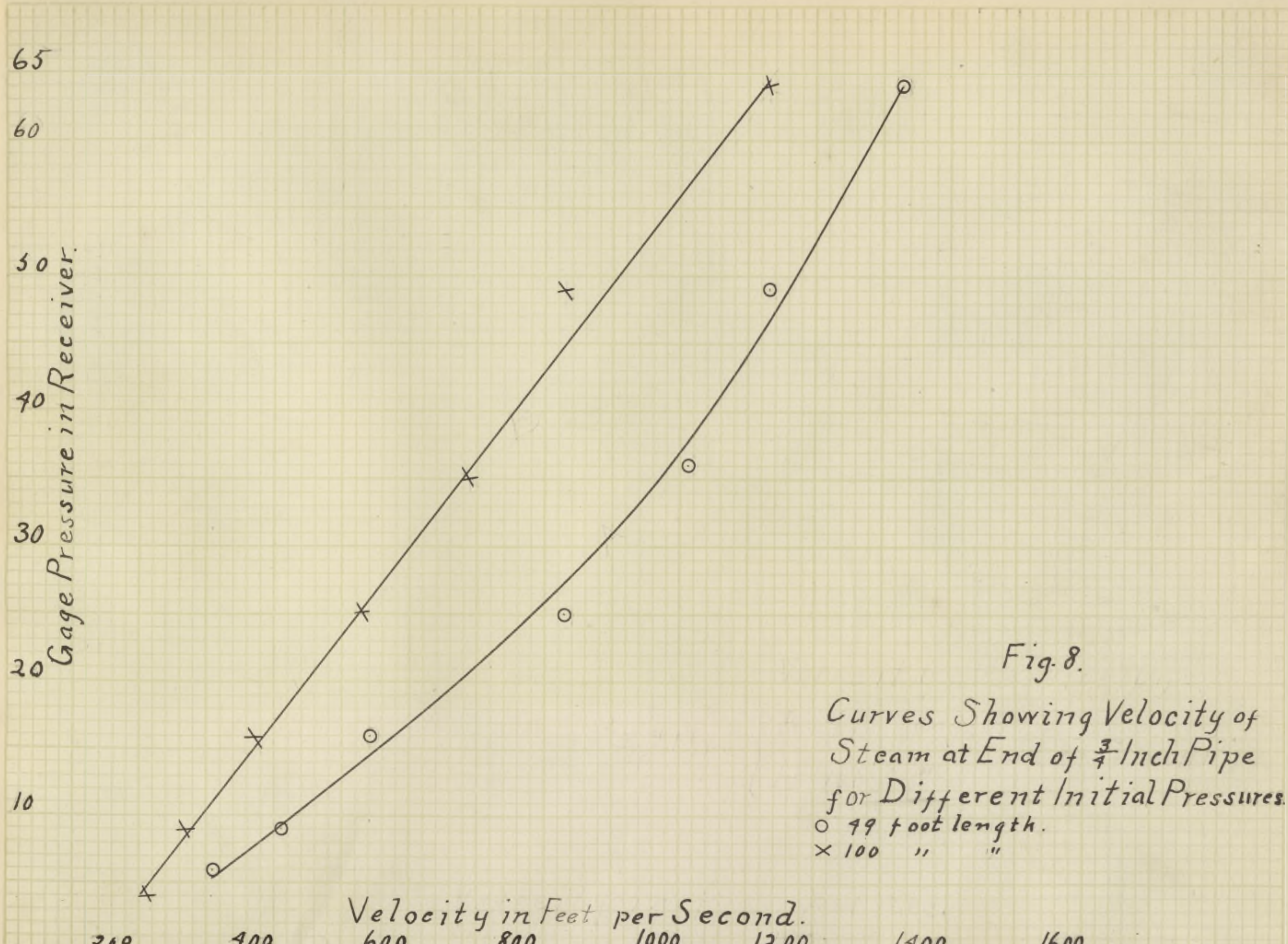


Fig. 8.

Curves Showing Velocity of Steam at End of $\frac{3}{4}$ Inch Pipe for Different Initial Pressures.

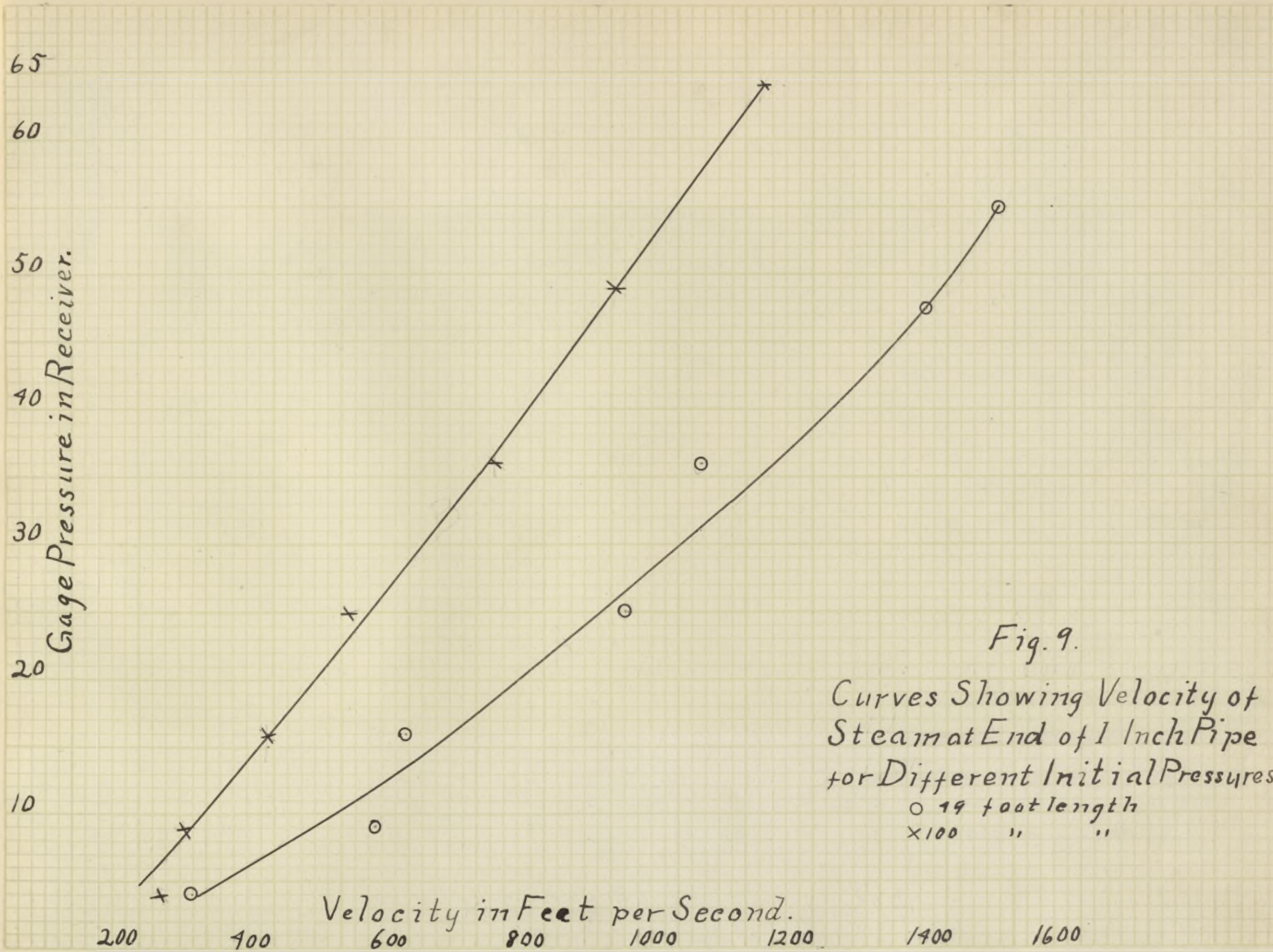


Fig. 9.

Curves Showing Velocity of Steam at End of 1 Inch Pipe for Different Initial Pressures.

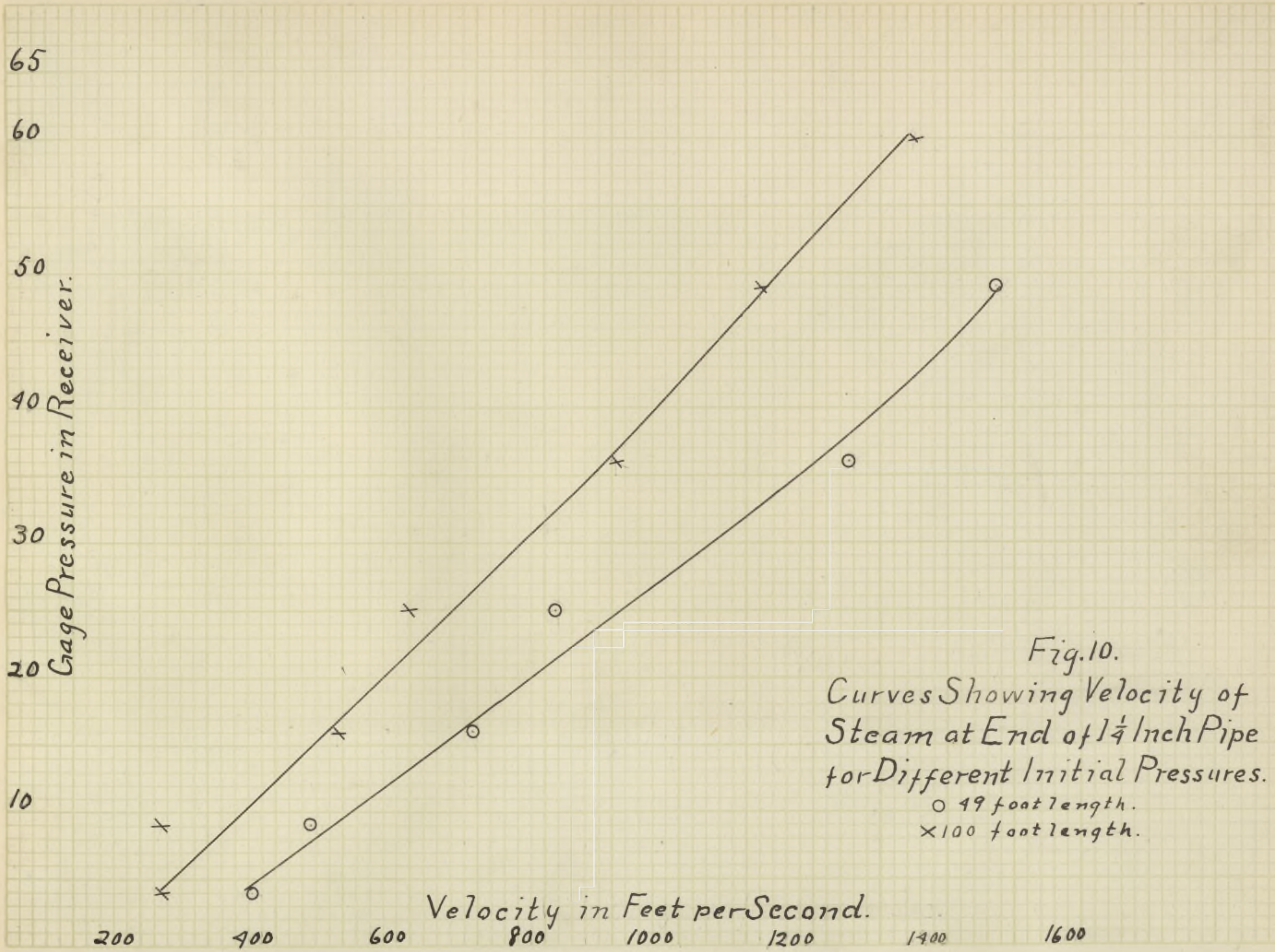


Fig. 10.
Curves Showing Velocity of Steam at End of $1\frac{1}{4}$ Inch Pipe for Different Initial Pressures.

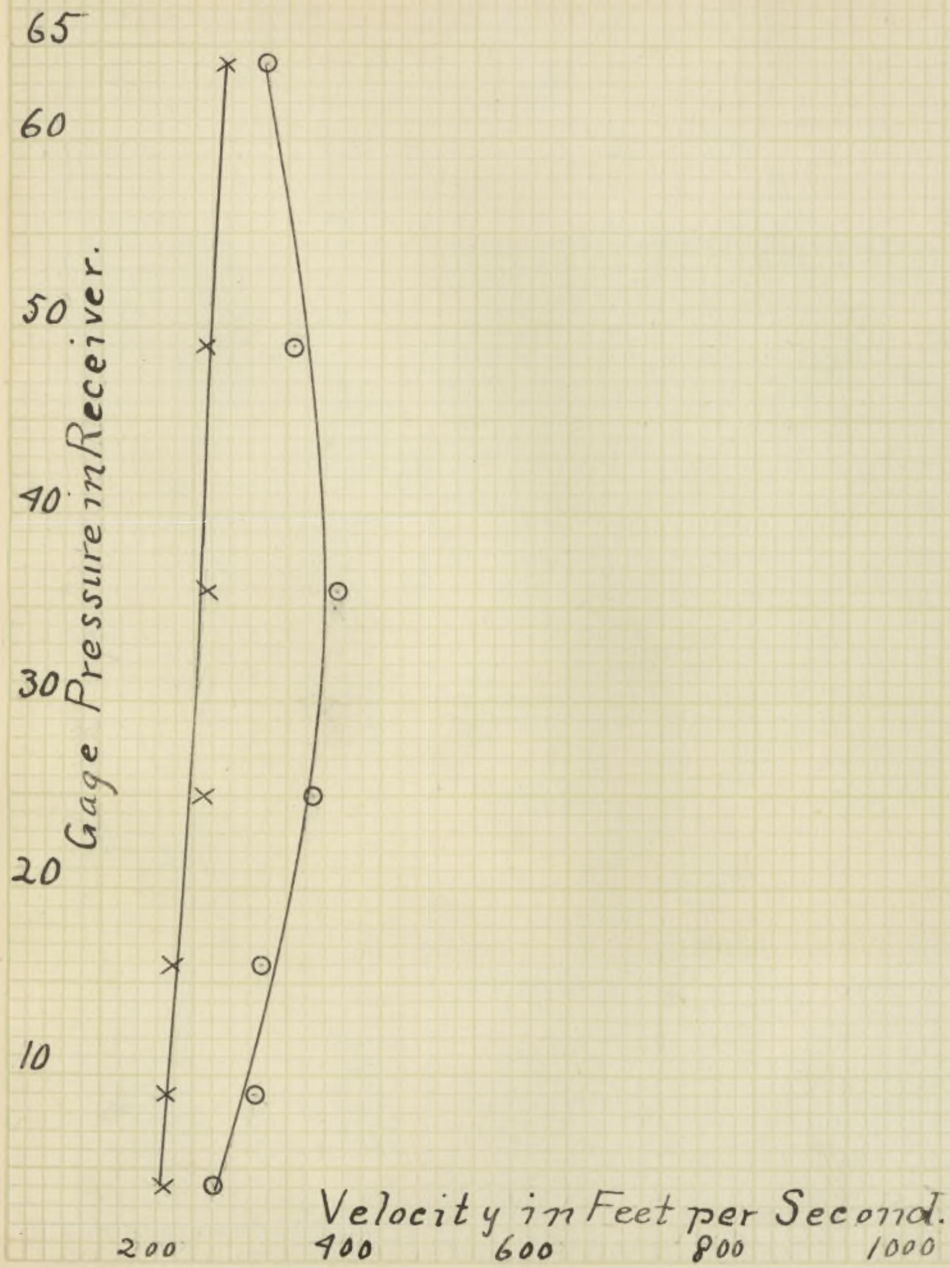


Fig. 11.
Curves Showing Velocity of Steam at Entrance of $\frac{3}{4}$ Inch Pipe for Different Initial Pressures.

○ 49 foot length.
× 100 " "

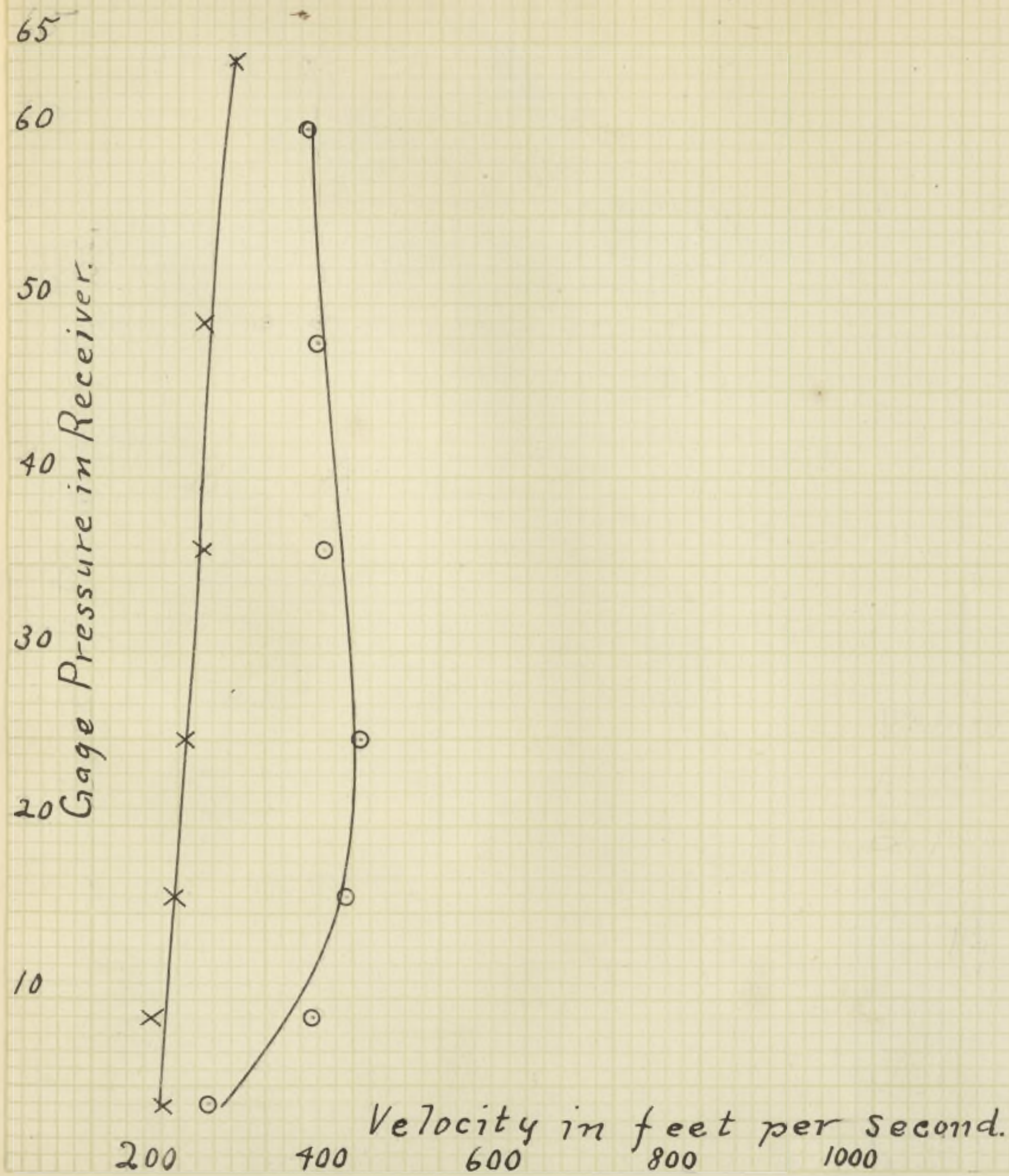


Fig. 12.
Curves Showing Velocity of Steam at Entrance of 1 Inch Pipe for Different Initial Pressures.

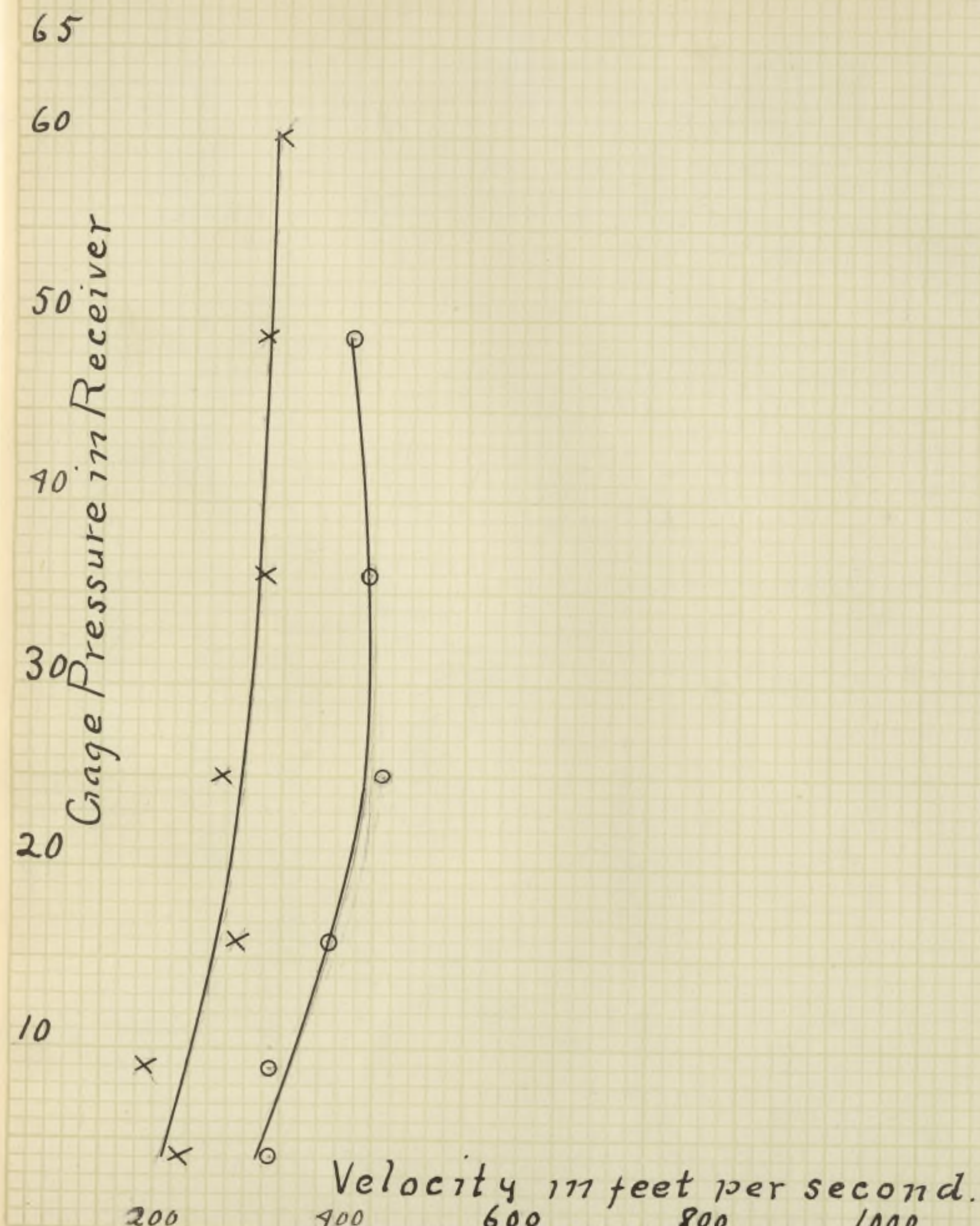


Fig. 13.

Curves Showing Velocity of Steam at Entrance of $1\frac{1}{4}$ Inch Pipe for Different Initial Pressures.

o 49 foot length.

× 100 " "

Table I.

Pressures at Which Experiments Were Made on the Different Pipes.

Diamater. Inches.					
$\frac{3}{4}$		1		$1\frac{1}{4}$	
Length. Feet					
49	100	49	100	49	100
6	4	4	4	4	4
9	9	9	9	9	9
16	16	16	16	16	16
25	25	25	25	25	25
36	36	36	36	36	36
49	49	47.5	49	49	49
64	64	55	64	---	60

Experiments at 9, 20, 23, two at 25, three at 49, one at 60.8 and 62 pounds pressure were made on the $\frac{3}{4}$ inch pipe 49 feet long.

Table II.

Experiments on $\frac{3}{4}$ Inch Pipe 49 Feet Long.

Boiler-Pressure.	Receiver Pressure.	Height of Barometer, Inches.	Temperature of External air, F.	Weight of Water Evaporated in 30 Minutes, Obtained from Calibration Curve, lbs.	Per Cent of Moisture in Steam.	Weight of Dry Steam Flowing in 30 Minutes = ExFx.87.	Weight of Steam in 30 Minutes by Formula.
A	B	C	D	E	F	G	H
50	6	29.86	66	91	0.0	79	54
72	9	29.99	45	131	2.3	106	72
74	16	29.99	48	165	3.4	139	108
68	25	29.86	62	248	1.1	213	154
67	36	29.90	43	339	3.0	285	205
72	49	29.41	56	378	6.7	303	266
77	64	29.90	42	444	11.6	342	335
72	9	29.86	61	138	2.6	117	72
54	20	29.86	66	232	0.0	202	---
73	23	29.69	60	252	10.6	213	---
66	25	29.90	46	255	1.4	---	154
70	33.5	29.69	60	315	10.6	245	---
69	49	29.90	45	352	20.5	---	266
64	49	29.86	70	416	15.0	---	266
68	49	29.90	43	445	25.8	---	266
68	60.8	29.40	58	558	26.8	360	325
69	62.3	29.86	66	461	24.2	302	---

Table III.

Experiments on $\frac{3}{4}$ Inch Pipe 100 Feet Long.

Boiler Pressure.	Receiver Pressure	Height of Barometer, Inches.	Temperature of External Air, F.	Weight of Water Evaporated in 30 Minutes, Obtained from Calibration Curve, lbs.	Per Cent of Moisture in steam.	Weight of Dry Steam Flowing in 30 Minutes = E x F x .87	Weight of Steam in 30 Minutes by Formula.
A	B	C	D	E	F	G	H
42	4	29.89	77	68	2.3	57	30
46	9	29.89	77	81	2.0	69	50
46	16	29.91	68	112	2.1	96	76
52	25	29.91	69	160	2.2	137	108
55	36	29.91	72	203	1.8	173	144
55	49	29.91	72	251	1.9	214	186
74	64	29.91	74	343	2.0	292	234

Table IV.

Experiments on 1 Inch Pipe 49 Feet Long.

Boiler Pressure.	Receiver Pressure.	Height of Barometer, Inches.	Temperature of External Air, F.	Weight of Water Evaporated in 30 Minutes, Obtained from Calibration Curve, lbs.	Per Cent of Moisture in Steam.	Weight of Dry Steam Flowing in 30 Minutes = E x F x .87.	Weight of Steam in 30 Minutes by Formula.
A	B	C	D	E	F	G	H
60	4	29.92	46	153	3.0	126	88
56	9	29.92	48	268	3.8	231	147
65	16	29.92	42	315	14.3	244	222
62	25	29.92	41	532	7.7	427	312
78	36	29.92	38	597	8.9	473	420
74	47.5	29.94	45	676	10.9	572	531
80	55	29.94	78	743	4.6	617	596

Table V.

Experiments on 1 Inch Pipe 100 Feet Long.

Boiler Pressure.	Receiver Pressure	Height of Barometer, Inches.	Temperature of External Air, F.	Weight of Water Evaporated in 30 Min. Obtained from Calibration Curve, lbs.	Per Cent of Moisture in Steam.	Weight of Dry Steam Flowing in 30 Minutes = E X F X .87.	Weight of Steam in 30 Minutes by Formula.
A	B	C	D	E	F	G	H
30	4	29.89	70	104	1.8	89	61
35	9	29.89	72	129	1.3	111	103
65	16	29.85	70	193	3.0	164	154
64	25	29.85	64	279	12.6	212	217
65	36	29.85	72	406	14.2	304	292
65	49	29.85	72	476	8.7	379	379
78	64	29.85	70	633	4.8	525	479

Table VI.

Experiments on $1\frac{1}{4}$ Inch Pipe 49 Feet Long.

Boiler Pressure.	Receiver Pressure.	Height of Barometer, Inches.	Temperature of External Air, F.	Weight of Water Evaporated in 30 Minutes Obtained from Calibration Curve, lbs.	Per Cent of Moisture in Steam.	Weight of Dry Steam Flowing in 30 Minutes = E×F×.87.	Weight of Steam in 30 Minutes by Formula.
A	B	C	D	E	F	G	H
50	4	29.77	76	326	7.6	262	193
50	9	29.77	78	407	3.7	343	323
59	16	29.77	78	590	2.1	504	486
54	25	29.77	82	864	2.9	743	685
72	36	29.77	84	1079	3.2	908	921
82	49	29.77	84	1309	6.5	1065	1195

Table VII.

Experiments on $1\frac{1}{4}$ Inch Pipe 100 Feet Long.

Boiler Pressure	Receiver Pressure	Height of Barometer, Inches.	Temperature of External Air, F.	Weight of Water Evaporated in 30 Min. Obtained from Calibration Curve, lbs.	Per Cent of Moisture in Steam.	Weight of Dry Steam Flowing in 30 Minutes $= E \times F \times .87$	Weight of Dry Steam in 30 Minutes by Formula.
A	B	C	D	E	F	G	H
31	4	29.83	78	202	4.6	168	135
30	9	29.83	79	215	10.0	169	226
40	16	29.83	80	449	8.8	356	340
43	25	29.83	83	538	7.4	433	478
57	36	29.83	81	803	6.5	653	644
80	49	29.98	63	967	6.0	798	836
82	60	29.98	64	1179	5.0	974	998

Table VIII.

Weight of Steam Flowing per Minute by Experiment.

Gage Pressure in Receiver	Diamater, Inches.					
	3/4		1		$1\frac{1}{4}$	
	Length, Feet.					
	49	100	49	100	49	100
4	- - - -	1.8	4.12	2.98	8.73	5.59
9	3.54	2.29	7.69	3.68	11.43	5.63
16	4.64	3.19	8.12	5.48	16.79	11.86
25	7.11	4.55	14.24	7.08	24.77	14.44
36	9.51	5.77	15.78	10.12	30.28	21.78
49	10.11	7.13	- - -	12.62	35.49	26.59
64	11.38	9.74	- - - -	17.49	- - - -	- - -
6	2.63					
47.5			19.06			
55			20.56			
60						32.48

Table IX.

Weight of Steam per Minute by Formula.

Gage Pressure in Receiver	Diamater of Pipe, Inches.					
	$\frac{3}{4}$		1		$1\frac{1}{4}$	
	Length, Feet.					
	49	100	49	100	49	100
4	1.43	1.02	2.92	2.04	6.43	4.5
9	2.43	1.70	4.88	3.42	10.77	7.54
16	3.66	2.56	7.34	5.14	16.20	11.34
25	5.15	3.61	10.34	7.24	22.82	15.97
36	6.93	4.85	13.92	9.74	30.70	21.49
49	9.00	6.30	18.06	12.64	39.84	27.89
64	11.07	7.75	22.80	15.96	50.28	35.20
6	1.87					
47.5			17.52			
55			19.95			
60						32.25

Table X.

Velocity of Steam in Feet per Second at End of Pipe.

Gage Pressure in Receiver	Diamater of Pipe, Inches.					
	3/4		1		1 1/4	
	Length, Feet.					
	49	100	49	100	49	100
4	----	215	289	233	362	232
9	411	262	553	265	449	232
16	540	371	597	393	696	492
25	827	530	1027	509	816	599
36	1106	687	1134	728	1255	903
49	1176	830	----	907	1472	1100
64	1324	1132	----	1258	----	---
6	305					
47.5			1370			
55			1478			
60						1347

Table XI.

Velocity of Steam in Feet per Second at Entrance of Pipe

Gage Pressure in Receiver.	Diamater of Pipe, Inches.					
	3/4		1		1 1/4	
	Length, Feet					
	49	100	49	100	49	100
4	----	172	237	182	290	186
9	264	171	356	170	289	150
16	273	188	295	199	352	249
25	329	211	409	207	409	238
36	351	213	359	230	398	286
49	301	214	---	232	377	282
64	278	238	---	264	---	---
6	223					
47.5			361			
55			348			
60						297